Optimal strategy for seabed 3D mapping of AUV based on imaging sonar

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***Abstract*—An imaging sonar loses information of elevation angle while a mapping process. To overcome this limitation, the motion of the autonomous underwater vehicle (AUV) can be used to obtain 3D information using the imaging sonar. In this paper, we propose a two-stage mapping strategy for accurately generating underwater 3D maps based on an imaging sonar. It consists of searching and scanning stage. In the scanning stage, multi-directional scanning is performed on an object. To process 3D point cloud data obtained by multi-directional scanning, we propose a polygonal approximation method. This method reduces the uncertainty of 3D point cloud data by extracting intersection area of multiple data groups. To verify the feasibility of proposed strategies, we conducted indoor tank experiments using a hovering-type AUV 'Cyclops' and acoustic lens-based multibeam sonar (ALMS) 'DIDSON'.**

Keywords*— *Imaging sonar, Hovering-type AUV, Underwater 3D map generation, Underwater 3D point cloud, Polygonal approximation

1. Introduction

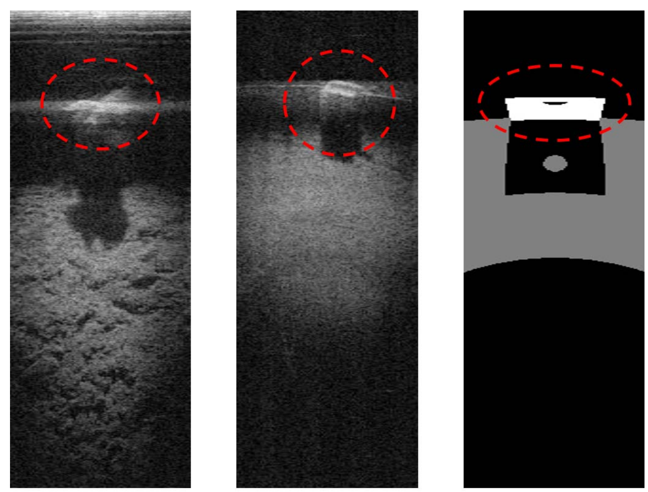
In many underwater missions, 3D information of objects or surroundings can be an important role. There are several ways to obtain 3D information of the underwater environment, such as the use of multiple optical cameras, the use of laser and optical cameras together. However, the use of optical cameras is limited in dark and turbid conditions. In recent years, several methods have been developed to obtain 3D information of underwater environments using sonar systems rather than optical cameras [1].

Among these studies, a method was developed that can generate an underwater 3D point cloud data using acoustic lens-based multibeam sonar (ALMS) mounted on an autonomous underwater vehicle (AUV). This method took advantage of geometrical analysis of sonar and mobility of AUV [2]. However, this study only explained basic principles and conducted feasibility tests. It is difficult to use it for advanced techniques such as object recognition or underwater navigation. Therefore, scanning strategy and post-processing of 3D point cloud should be properly considered.

In this paper, we propose underwater 3D mapping method using AUV and 3D point cloud generation method. We analyze the parameters and factors affecting 3D mapping results. In addition, the AUV-based scanning strategy and 3D polygonal approximation method are proposed to overcome the limitation of the 3D point cloud generation method. The proposed strategies improve the accuracy and tolerance of sonar-based 3D mapping of AUV.

2. Background

The height of objects on the seabed is directly dependent on the elevation angle in the sonar coordinate system, which is lost in the 3D scene to 2D image projection. This confirms that we cannot measure the height of objects on the seabed using only a single sonar image. But, this problem can be solved by utilizing mobility of the vehicle and changes of highlight part in the sonar images.



(a) (b) (c)

Fig. 1. Examples of sonar image with highlight extension effect. In case of (a) sea trial, (b) indoor tank test, (c) sonar simulator

When the vehicle equipped with the ALMS moves over the seabed, the highlight and shadow regions of the sonar image vary. In particular, a case arises during the forward/ backward movement where the highlight falls in a range between the minimum mechanical observation distance (r_{emin}) and the minimum observation distance (r_{min}) set by the user. We defined this phenomenon as a highlight extension effect, which can be seen in many sonar images of the sea trial, indoor tank test and sonar simulator [3] as shown in Fig. 1.

By analyzing the changes in highlight and the ALMS geometry, the height profile for one horizontal scan-line in the sonar image can be calculated. Then, we can generate a 3D point cloud of underwater terrain through the flyover sonar motion over the object. This is similar to the algorithm of a line-scan laser in underwater.

However, this method has several critical problems. Since the highlight extension effect does not occur under all conditions, AUV should adaptively change the geometry relationship according to the dimension of the object. In addition, it is also the important limitation that only the point cloud data of the front and the upper surface of the object can be obtained. This causes information loss and uncertainty on the side surface and back surface of the object. This also means that 3D information of the object cannot be completely obtained with one scan.

3. Proposed Strategy

3.1. Conditions for accurate mapping

The sonar geometry occurring the highlight extension effect depends on several parameters such as the height of the object (h), the distance from seabed (H), and the tilt angle (t) of the ALMS. The range and condition of these parameters should be determined appropriately. Moreover, the AUV with sonar should actively move according to the changes of object and condition.

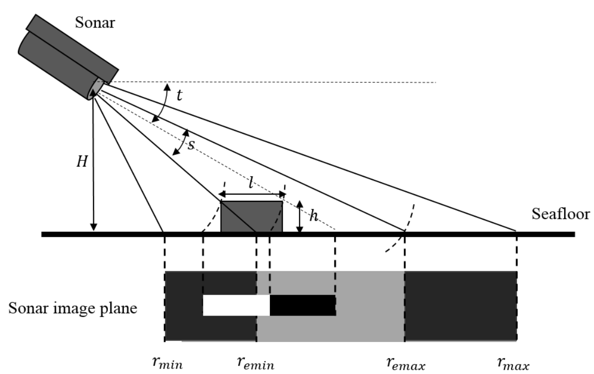


Fig. 2. Sonar geometry when the highlight extension effect occurs

The acoustic beams of ALMS have a finite vertical beam spread angle s, as shown in Fig 2. We can set several conditions and ranges as follows.

$$r_{emax} = \frac{H}{sin(t - \frac{s}{2})} < r_{max} \tag{1}$$

$$r_{emin} = \frac{H}{sin(t + \frac{s}{2})} > r_{min} \tag{2}$$

$$H > 2h \tag{3}$$

$$0^\circ < t < 45^\circ \tag{4}$$

(1) and (2) are descriptions of the sensor settings to generate the highlight extension effect. (3) means that the distance from seabed should be greater than the height of the object. The smaller the difference between H and h, the smaller t or the more approach of AUV are required to observe the object at the same depth level. Smaller t and smaller H make the shadow part of the object in the sonar image unusually long. The approach of AUV also causes problems by increasing the length of the object in the sonar image. (4) is a description of t of the ALMS. The larger t value, the smaller the reaching area of sonar beam at the same depth level. This can interfere with the occurrence of the highlight extension effect.

The analysis of sonar geometries can be done using the sonar simulator [4]. The sonar simulator provides predicted sonar images based on the position and pose of the sonar and the object. This will save time and cost of finding optimal geometric relationships.

3.2. Two-stage strategy for recognition of 3D information

We propose a strategy for obtaining 3D information of an object through two stages, which are searching stage and scanning stage.

In the searching stage, the AUV sets the range of sonar to a long range for scanning the large area. The AUV searches for objects with high altitude and long range from the seabed as shown in Fig. 3(a). Moreover, Algorithms for detecting objects in sonar images are also applied such as real-time object detection using artificial intelligence. When the AUV finds an object, we can extract the 2D position and the object height estimated by the highlight extension effect in the long-range situation.

In the scanning stage, the AUV approaches to the target object and scans in detail. The AUV sets the range of sonar to a short range for scanning the detailed shape. Then, the AUV starts to scan the object in multi-directional. To obtain 3D point cloud data through the highlight extension effect, flyover movement over objects is done in multiple angles by the AUV.

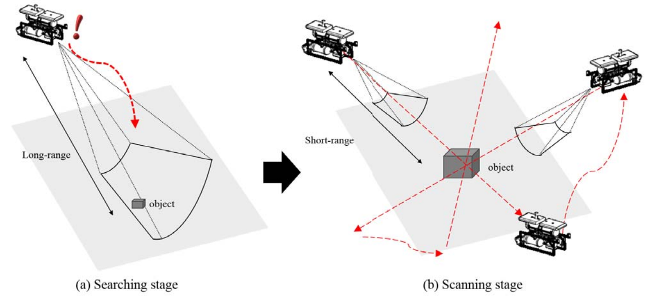


Fig. 3. Two stage strategy: searching stage and scanning stage

At least two scans of an object should be done to observe an object and perform the 3D reconstruction precisely. This is because the scanning method by the highlight extension effect is relatively accurate in the vertical direction rather than in the horizontal direction. The uncertainty in the horizontal direction is larger than those in the vertical direction. Therefore, it is necessary to scan at multiple angles to properly determine the shape of an object as shown in Fig. 3(b).

3.3. Polygonal approximation of 3D point cloud data

The scanning data in only one direction has only information on the front and top. Since there is no information on the side and the back side, reconstructed 3D shape by a single scanning becomes very inaccurate. Therefore, the 3D shape of the object must be estimated using the relationship between several 3D point cloud data obtained from multi-directional scanning.

The first step is to project 3D point cloud data groups onto a 2D X-Y plane. Computation between 3D data is not suitable for real-time operations because it requires a lot of computation time. Therefore, the analysis is calculated in two dimensions. The second step is to process the noise of the projected 2D data and to calculate the maximum overlapping polygon. The maximum overlapping polygon is the maximum intersection of data groups. This is the process of eliminating uncertainty between each data groups. The final step is the process of creating a 3D polygon using 2D point cloud data and height information inside the maximum overlapping polygon.

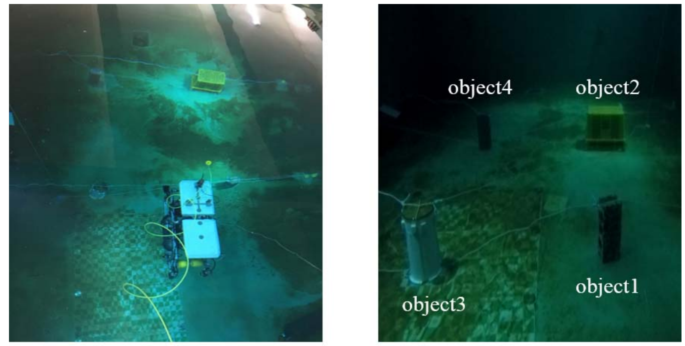
This method can reduce the uncertainty of the reconstructed 3D object shape. When new 3D point cloud data is received, the shape of the approximated 3D polygon can be updated by re-calculating the intersection area. As the number of scans and the variety of directions increase, the 3D object shape can be reconstructed more accurately.

4. Experiments

We conducted several experiments in an indoor tank to check the feasibility and accuracy of the proposed method. Several artificial objects were installed on the floor of an indoor tank as shown in Fig. 4. Then, the floor was scanned by a hovering-type AUV 'Cyclops' [5] equipped with ALMS 'DIDSON' [6] as shown in Fig. 5. The ALMS provides us real-time sonar video which has 512 by 96 resolution with the spread angle of 14 deg.

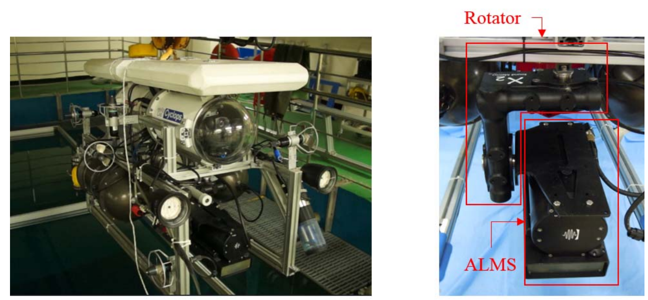
4.1. Unidirectional scanning experiment

Based on the proposed parameter analysis, we determined the parameters of ALMS geometry appropriately and scanned objects. The distance from seabed (H) and the tilt angle (t) were set as 1.42 m and 30 deg. The minimum mechanical observation distance (r_{emin}) and minimum mechanical observation distance (r_{emax}) were set as 1.25 m and 6.25 m.



(a) (b)

Fig. 4. (a) Indoor tank experiment with hovering-type AUV 'Cyclops' (b) Arrangement of artificial objects



(a) (b)

Fig. 5. (a) View of hovering-type AUV 'Cyclops' (b) Acoustic lens-based multibeam sonar mounted on Cyclops

Each object was scanned one by one from only the front. As a result, we obtained a 3d map of the indoor tank as shown in Fig. 6. The height and width of each object were different. However, only rough shapes were scanned and the shapes are inaccurate compared with actual objects.

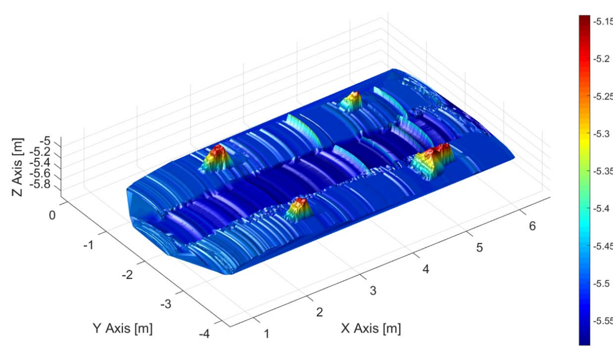


Fig. 6. 3D reconstruction result of unidirectional scanning experiment.

4.2. *Multi-directional scanning experiment*

Several Experiments were also conducted to analyze the precise scan results for one object. The AUV scanned one object (brick, 'object1 in Fig. 4(b)) in several directions not only one direction. Fig. 7 shows the 3D point cloud data of brick and the trajectory of the AUV. The AUV scanned first in the front, second in the 90° difference from the front, third in the 135° difference from the front.

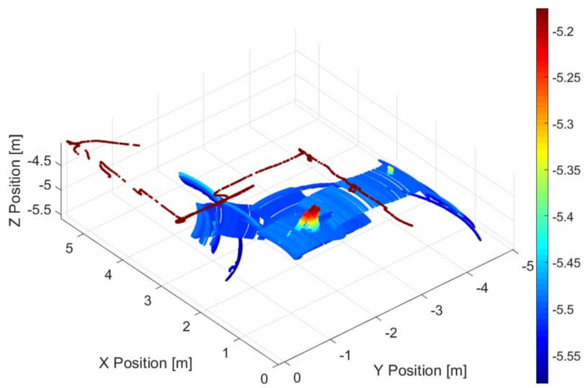


Fig. 7. AUV's trajectory and 3D point cloud data of multi-directional scanning experiment

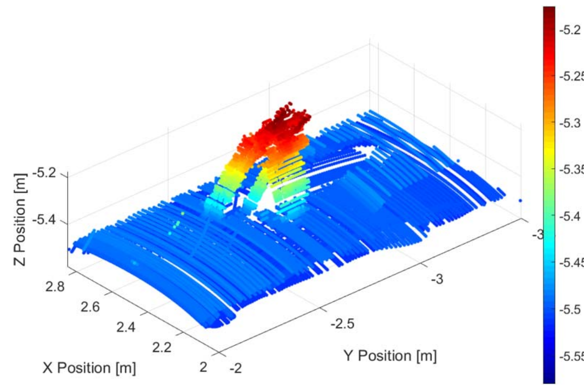
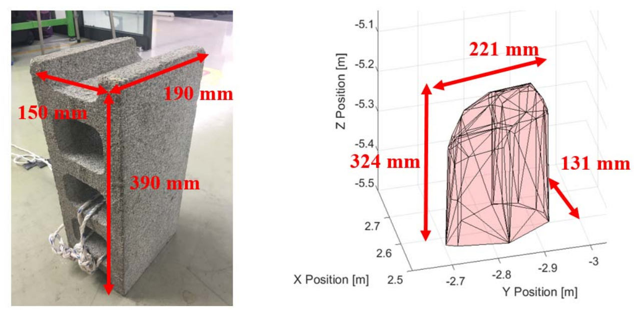


Fig. 8. Reconstructed 3D point cloud data for brick by multi-directional scan

Fig. 8 shows the detailed result of raw 3D point cloud data for brick after multi-directional scanning. Because the brick was scanned in three directions, all three groups of 3D point cloud data were superimposed. The undesired slope generation phenomenon, which is one of the disadvantages of utilizing the highlight extension effect, was shown. This slope data is erroneous data due to continuous motion of the AUV in the object direction. The shape of the brick was reconstructed incompletely, but the height information of brick was well reconstructed.



(a) (b)

Fig. 9. Comparison of brick's size. (a) shape and size of real brick. (b) shape and size of reconstructed 3D polygon by proposed method.

4.3. *3D polygon generation from 3D point cloud data*

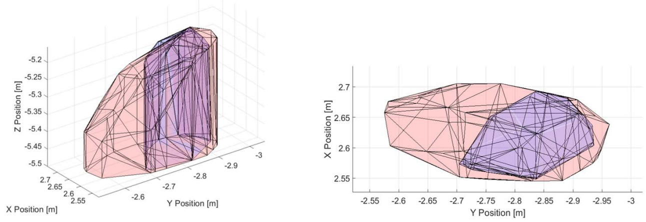
The 3D reconstruction results of multi-directional scanning experiment for one brick showed the inaccuracy of shape. To improve this result, we generated a 3D polygon using the groups of raw 3D point cloud data and the proposed method. The intersection area was calculated by projecting the three groups of 3D point cloud data onto a 2D X-Y plane. As a result, undesired slope data with no overlapping areas were isolated. Using the height information and the shape information approximated by the polygon, the 3D polygon of brick was reconstructed as shown in Fig. 9(b).

Fig. 9 showed the comparison results between the reconstructed 3D polygon and the actual brick. As a result, the actual brick was 150 mm, 190 mm and 390 mm in width, length and height respectively. The reconstructed 3D polygon was 131 mm, 221 mm and 324 mm in width, length and height respectively.

We verified the validity of the multi-directional scanning method based on the proposed two-stage strategy. The reconstruction result of the 3D polygon, which used a single group of 3D point cloud data from unidirectional scanning experiment, was compared with the result of multi-directional scanning experiment. Fig. 10 shows the comparison result. The result of unidirectional scanning contained undesired slope data, and both size and shape of 3D polygon were different from actual brick. Multi-directional scanning reduced the uncertainty of shape of the reconstructed 3D polygon by obtaining 3D point cloud data in various directions.

5. Future work

The proposed strategy is related to the detection and scanning of underwater objects. We will improve our detail method and utilize it to the navigation of AUV. This method can be used to correct the drift error of AUV by finding



(a) (b)

Fig. 10. Comparison of unidirectional scan results(red) and multi-directional scan results(purple). (a) comparison of 3D shape. (b) comparison of 2D projection shape.

unknown objects and using it as a natural landmark. In addition, it can be fused with underwater laser scanning method to achieve precise 3D reconstruction of underwater objects.

6. Conclusion

We presented a strategy to generate the underwater 3D map using AUV and ALMS. First, the parameters and factors affecting the 3D mapping are shown by the analysis of the geometry between the ALMS and the object. Second, the two-stage strategy for the path of AUV is proposed to overcome the limitation of the 3D point cloud generation method. Finally, the polygonal approximation algorithm was developed as a method for processing several 3D point cloud group obtained through a two-stage strategy. The proposed strategies were tested by the indoor tank experiments. The actual object and reconstructed 3D polygon were similar in size and shape.

Acknowledgement

This research was supported by the MSIT(Ministry of Science and ICT), Korea, under the ICT Consilience Creative program(IITP-2017-R0346-16-1007) supervised by the IITP(Institute for Information& communications Technology Promotion). This research was a part of the project titled 'Gyeongbuk Sea Grant', funded by the Ministry of Oceans and Fisheries, Korea. This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2017R1A5A1014883).

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